Enriching the IGM through Outflows to Cosmic Filaments

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AGN Outflows and chemical enrichment

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AGN outflows

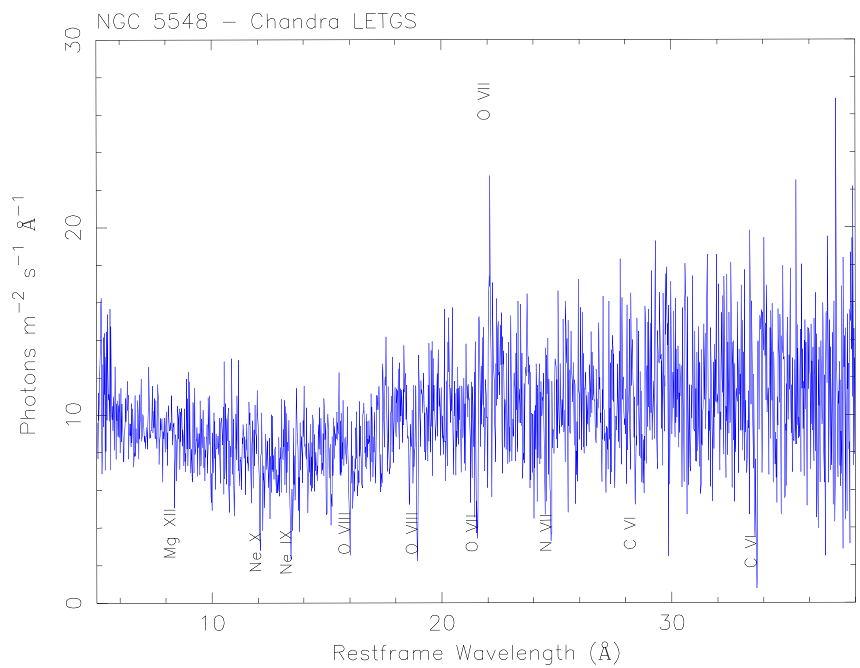
Importance of AGN outflows

(adapted from talk Jerry Kriss @ Utrecht conference)

- May affect dispersal heavy elements into IGM & ICM (e.g. Cavaliere et al. 2002; Scannapieco & Oh 2004)
- Influence ionisation structure IGM (Kriss et al. 1997)
- Intertwined with evolution host galaxy (e.g. Silk & Rees 1998; Wyithe & Loeb 2003)
- Not sure about how outflows created, their structure, mass & energy: *key question: do outflows escape confines of host galaxy?*
- Crucial to understand working central engine: central engine, energy budget
- Low-z AGN are the nearest & brightest, so best objects to study

Study outflows: need high spectral resolution

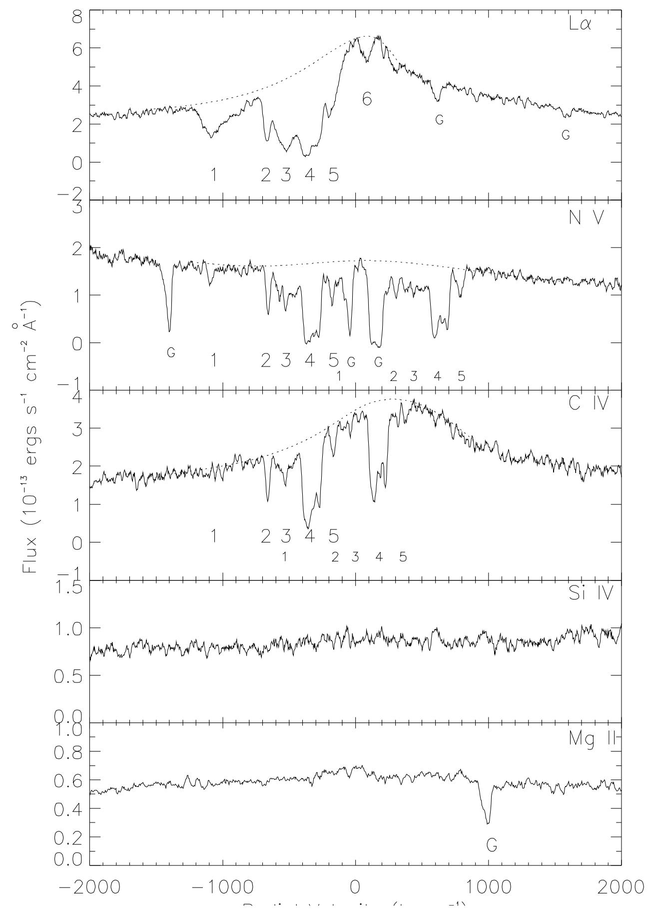
- Only with gratings detailed study of physics warm absorbers possible
- NGC 5548 first Seyfert ever observed at high spectral resolution (Dec. 1999, Chandra LETGS)
- Lots of absorption lines from different ions
- Shows importance of high resolution



Kaastra et al. 2000

Complex velocity structure

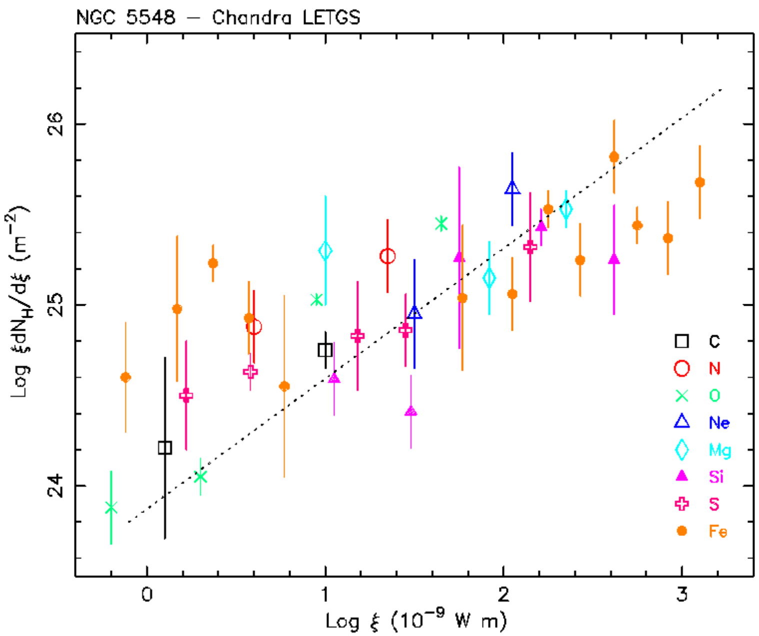
- Example: STIS spectra NGC 5548 (Crenshaw & Kraemer 1999) show 5 velocity components:
- Nr 1 high -1040 km/s
- Nr 2 med -667 km/s
- Nr 3 med -530 km/s
- Nr 4 med -336 km/s
- Nr 5 low -160 km/s



Radial velocity (km/s)

Complex ionisation structure

- Gas at multiple ionisation parameters
- Hot debate: continuous distribution, or multiple (2 or 3) discrete components in pressure equilibrium?



Steenbrugge et al. 2005

Mass loss through the wind

$$\dot{M}_{loss} = \Omega m_p n r^2 v \qquad n r^2 \cdot v = (L/\xi) \cdot v$$

$$\dot{M}_{loss} < \dot{M}_{acc} \qquad L = \eta \dot{M}_{acc} c^2$$

$$\Omega < \frac{(\xi / v)}{\eta m_p c^2}$$

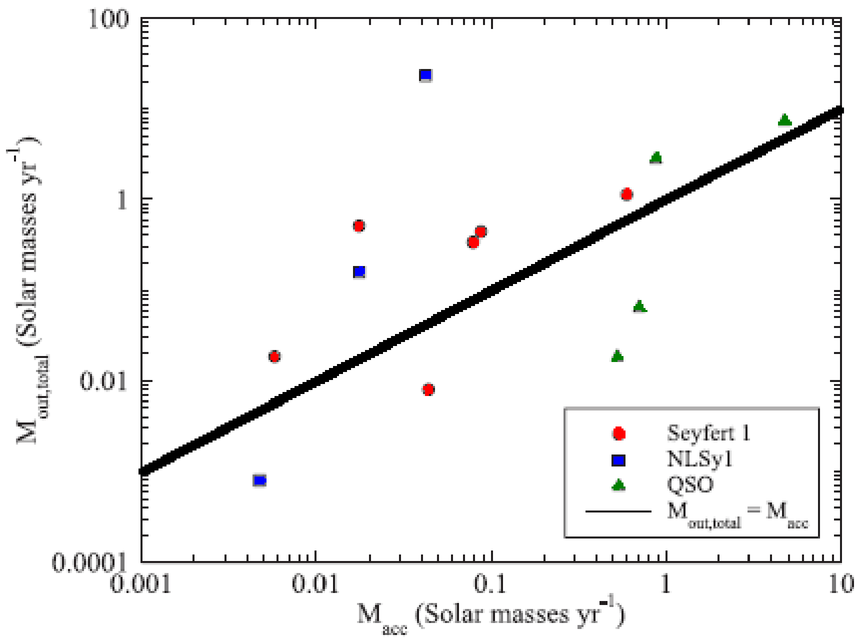
v (km/s)	-166	-1040
ξ=1	0.0007	0.0001
ξ=1000	0.7	0.1

Mass outflow rate

(Blustin et al. 2005)

- Assumption 1: solid angle 1.6 sr
- Assumption 2: momentum outflow = absorbed momentum radiation

✂➔Outflowing mass comparable to accreted mass



Importance of reverberation studies

Spherical shell:

Kinetic luminosity ~½ $\Omega R N_H m_p v^3$

$\Omega = O(\pi)$ from fraction of S1 with absorber

V measured from spectrum

N_H measured from spectrum

R unknown

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How to estimate R: reverberation

- If L increases for gas at fixed n and r, then $\xi = L/nr^2$ increases

✂ ➔ change in ionization balance

✂ ➔ column density changes

✂ ➔ transmission changes

- Gas has finite ionization/recombination time t_r (density dependent as $\sim 1/n$)

✂ ➔ measuring delayed response yields $t_r \rightarrow n \rightarrow r$

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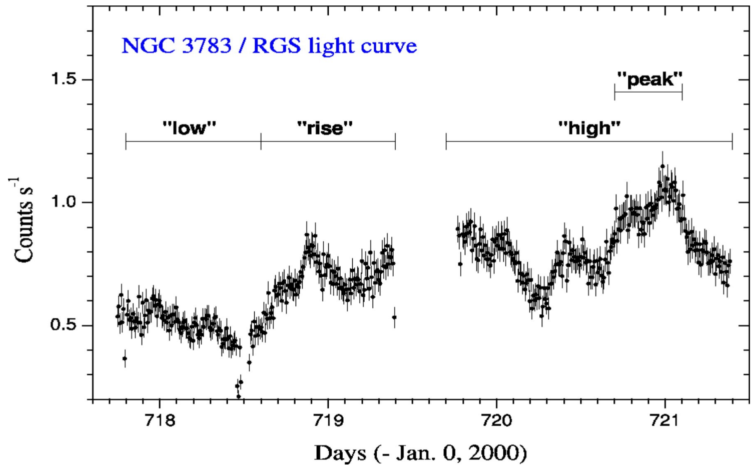
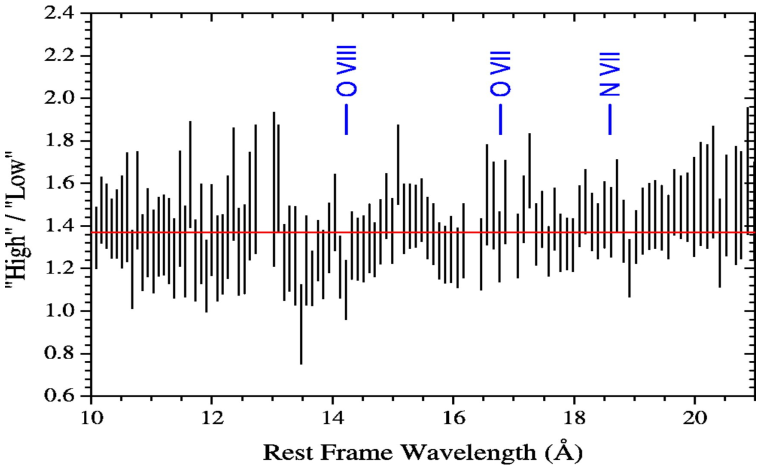
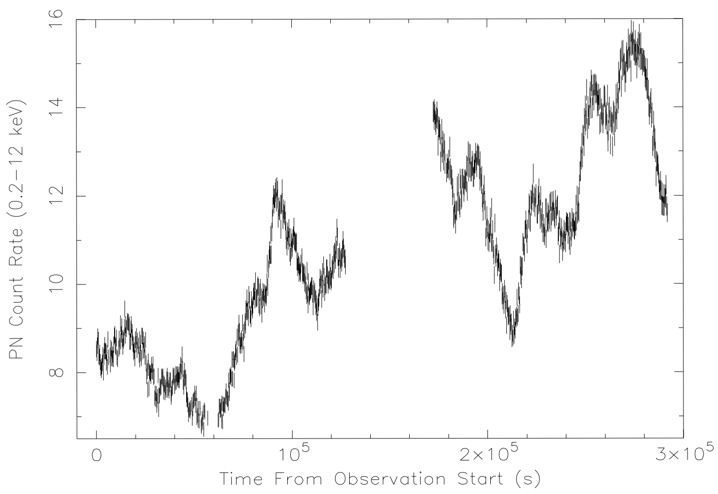
Reverberation: NGC 3783

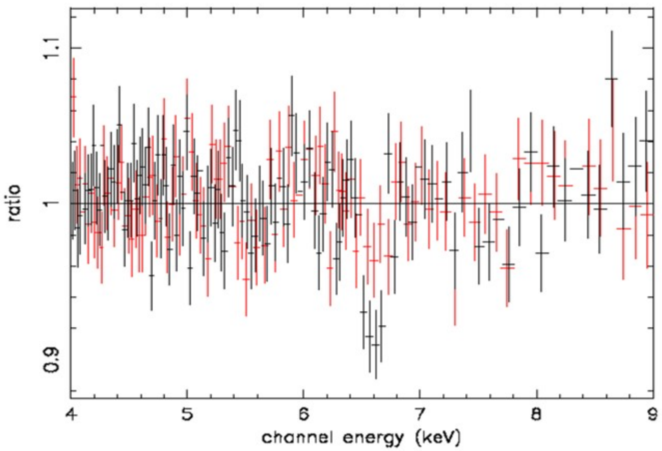




- RGS data (Behar et al. 2003): no change in Warm absorber ➔ n<300 cm^{-3}, r>10 pc.

Reverberation II: NGC 3783





- EPIC data (Reeves et al. 2003): change in

Warm absorber (larger columns) ➔ $n>10^8\ cm^{-3}$, $r<0.02$ pc.

➔ What to make out of this?

➔Urgent need of more data!

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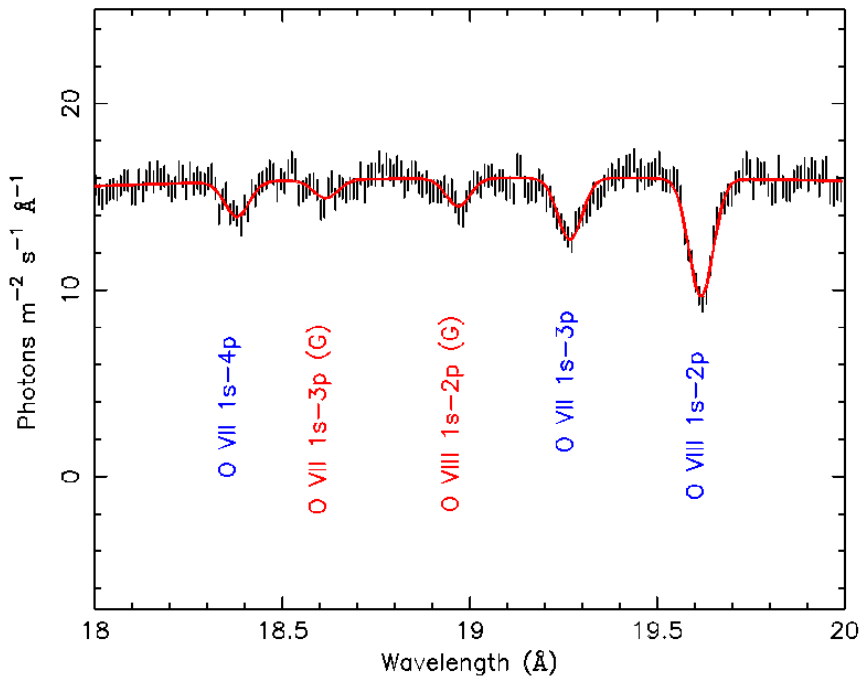
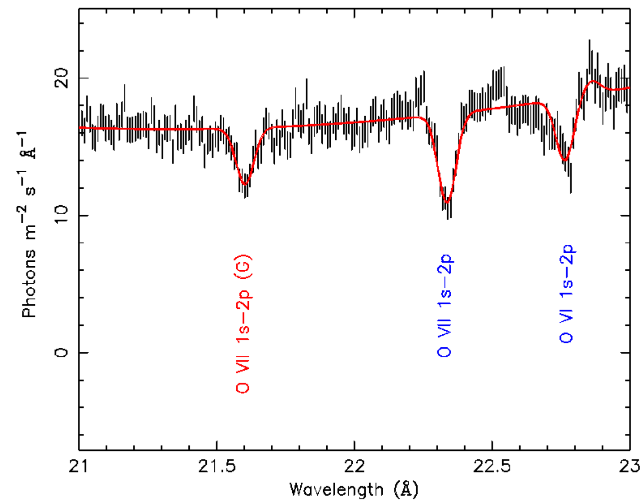
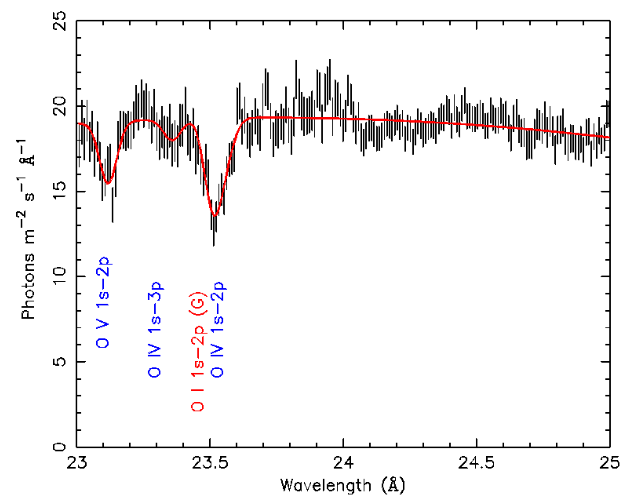
Mrk 509 campaign

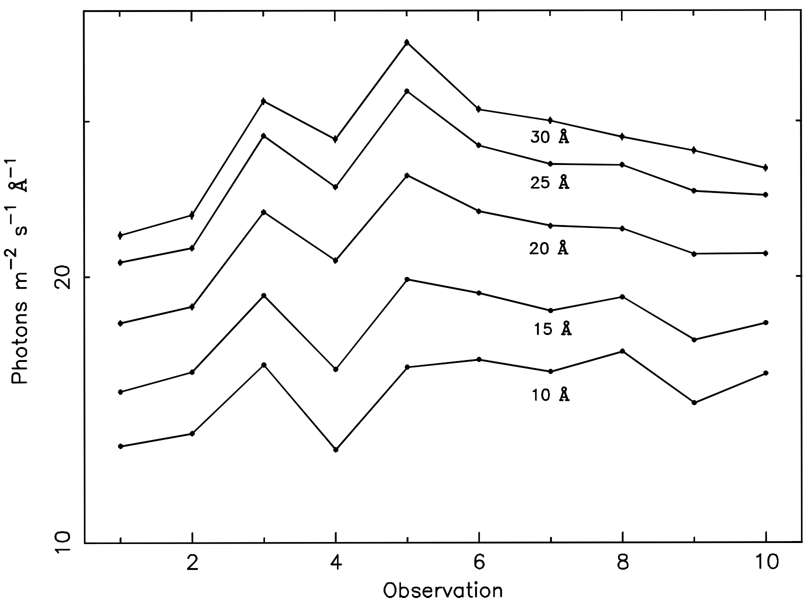
- 600 ks RGS+EPIC+OM XMM-Newton = 10 x 60 ks, 4 days spacing
- Simultaneous Integral, 1.2 Ms
- Chandra LETGS 170 ks + HST/COS spectra
- Swift monitoring in between & before
- Optical/IR coverage WHT & Pairitel
- One of biggest campaigns on AGN ever

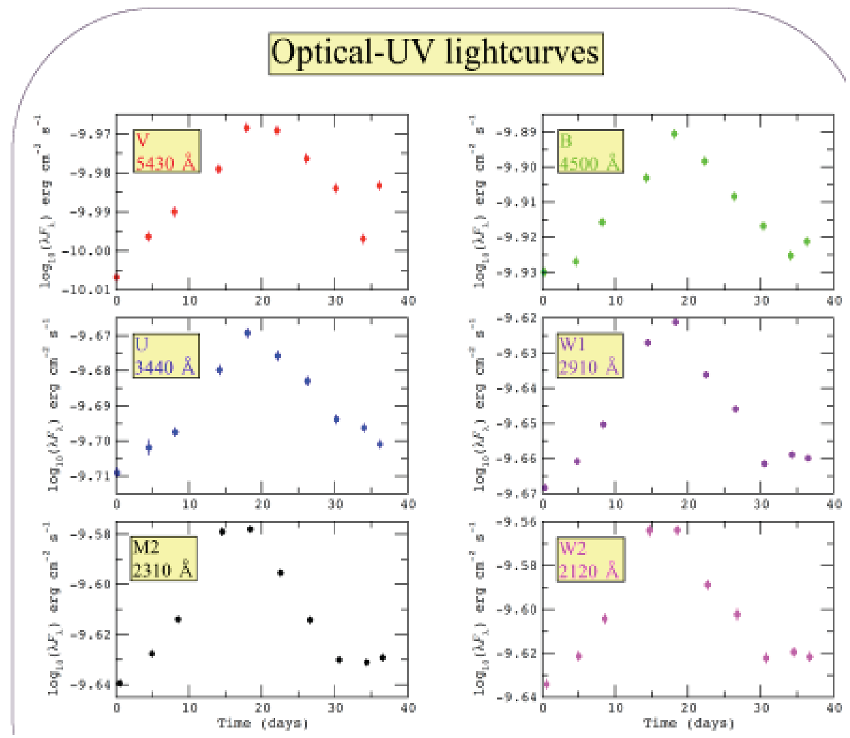

Photons m−2 s−1 Å−1
Wavelength (Å)
18
18.5
19
19.5
20
0
10
20
O VII 1s−4p
O VII 1s−3p (G)
O VIII 1s−2p (G)
O VII 1s−3p
O VIII 1s−2p


Photons m−2 s−1 Å−1
Wavelength (Å)
21
21.5
22
22.5
23
0
10
20
O VII 1s−2p (G)
O VII 1s−2p
O VI 1s−2p


Photons m−2 s−1 Å−1
Wavelength (Å)
23
23.5
24
24.5
25
0
5
10
15
20
25
O V 1s−2p
O IV 1s−3p
O I 1s−2p (G)
O IV 1s−2p

All ingredients are there…





Courtesy Missagh Mehdipour

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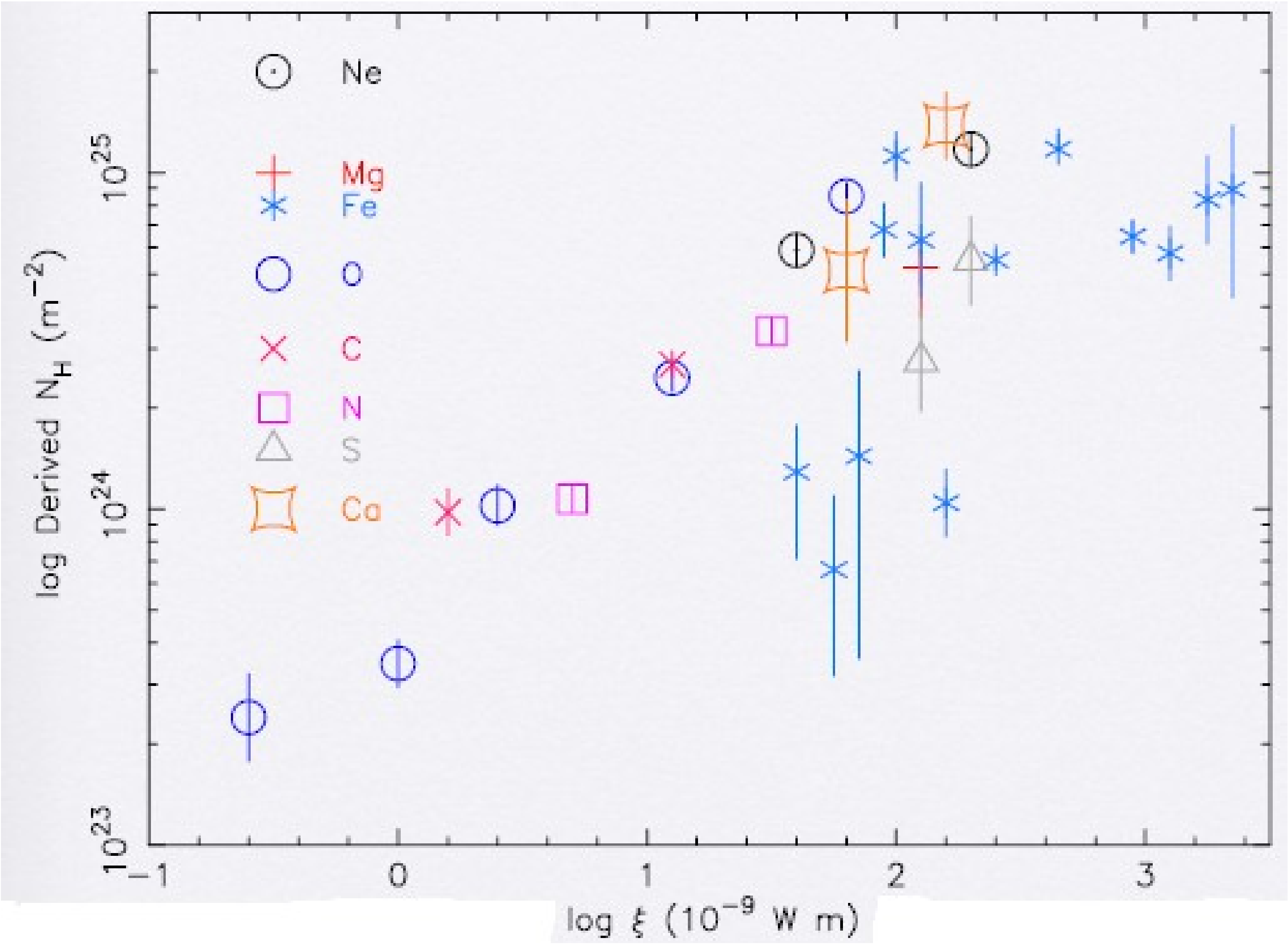
And of course do not forget this:

- AGN outflows have chemical composition core galaxy (modified by AGN environment, star formation?)
- Hard to measure in emission (systematics, multi-region, etc.)
- First reliable determination from UV spectra warm absorber in Mrk 279 (Arav et al. 2007:
- C 2.7±0.7, N 3.5±1.1, O 1.6±0.8

Abundances Mrk 509



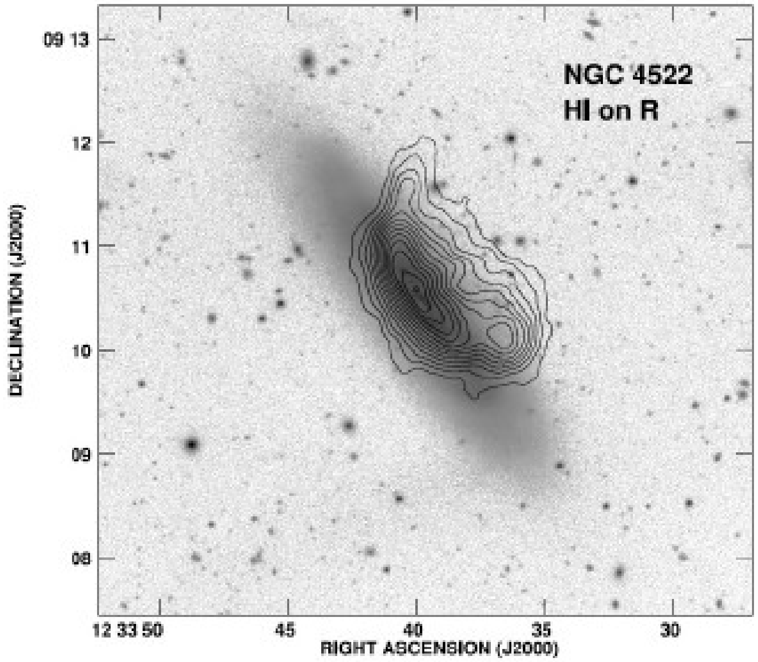
Enrichment in clusters of galaxies

Importance clusters of galaxies for abundance studies

- Largest bound structures
- Fair samples of the Universe
- Deep potential wells, retains most of the gas
- Hot gas: no significant “hiding” of metals in dust (& more gas than stars)
- Spatial extent allows mapping

How to get metals in clusters?

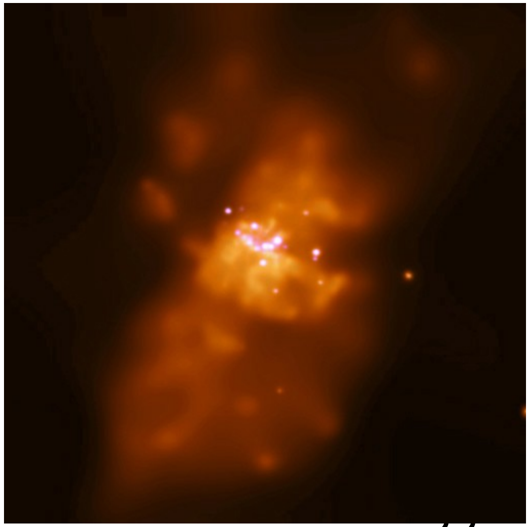
- Primordial gas mainly H & He
- Ram pressure stripping



Galactic winds

- Massive stars born in groups
- Sometimes many SN explosions in relatively short time
- Combined power may blow gas out of galaxies

M 82, optical



M 82, X-ray

Galaxy-Galaxy interactions

- Close encounters may cause tidal tails
- Stars and gas torn away from galaxies
- Enriched gas enters intergalactic space

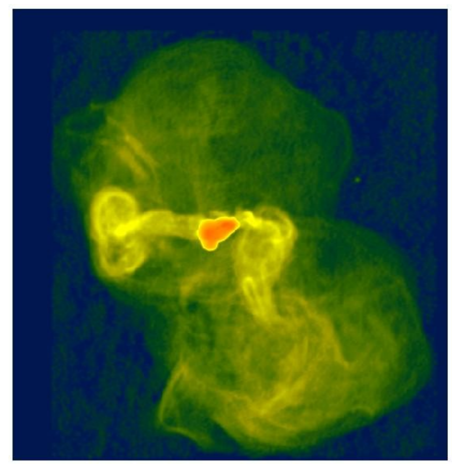
Antennae

(Sky & Telescope)

Giant outflows from active galaxies

- In compact clusters like M87, radio lobes show cool, enriched material levitated by the *AGN outflow*

X-ray

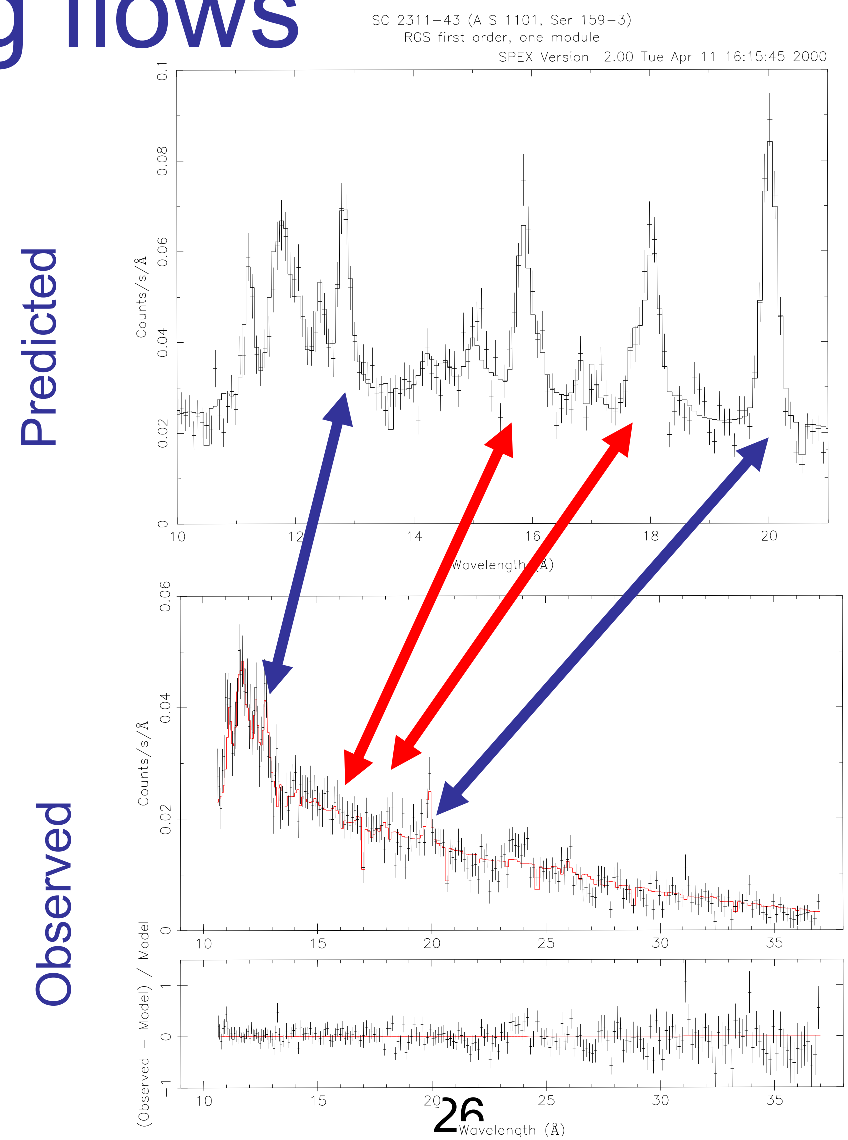


Radio

Cool core clusters

Predictions and observations of cooling flows

- Spectrum shows predicted Fe XXIII/XXIV and O VIII from kT=2.5 keV plasma
- But almost no Fe XVII/XVIII lines!



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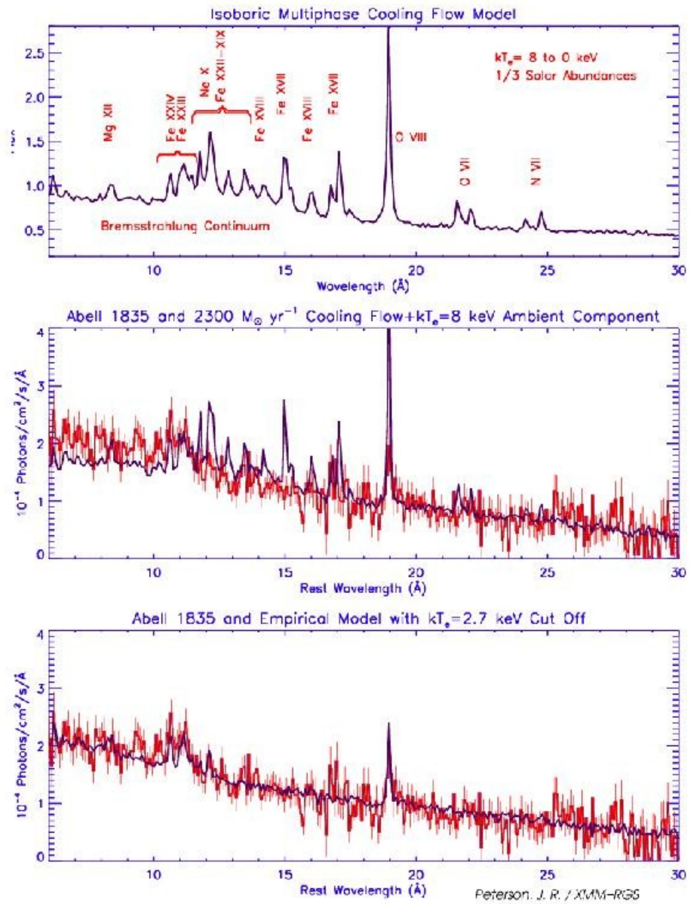
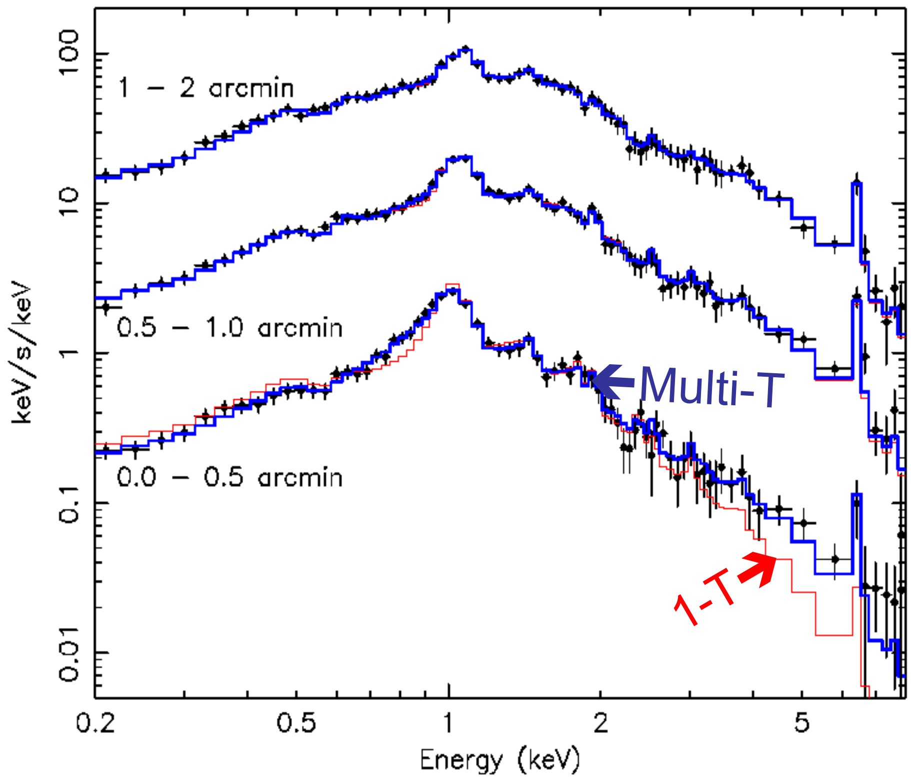
Other cases: A 1835
(Peterson et al. 2001)

- The same has been found in almost all RGS spectra of cool core clusters
- Many explanations have come up, but current idea is that predominantly AGN heating is causing the paucity of cool gas



Multiphase gas

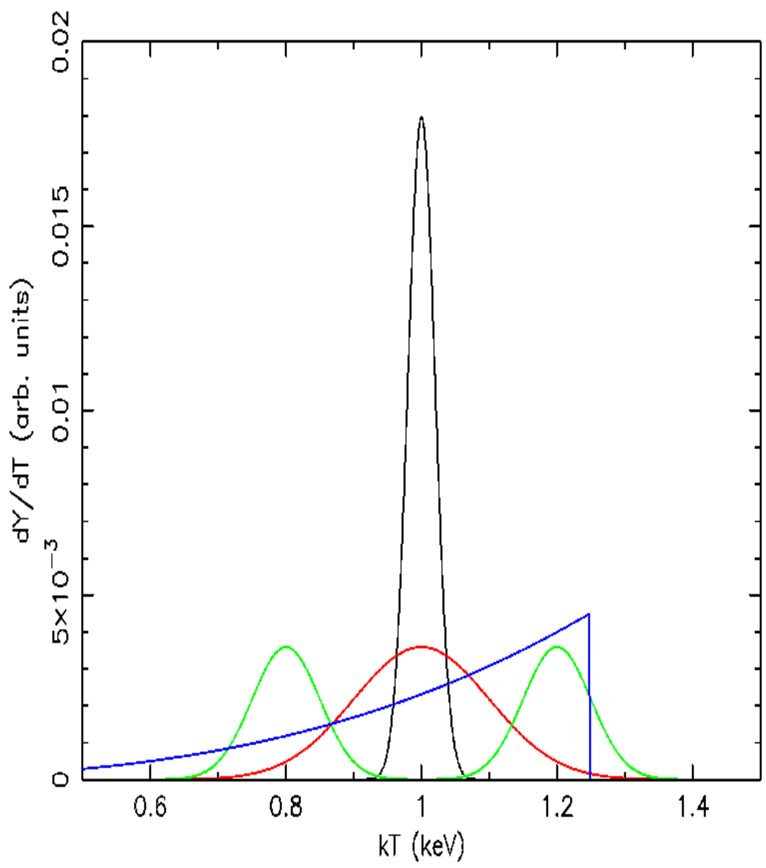
- Single T fits good first approximation
- But often χ^2 enhanced in central shells:
- Example: A 2052
- Need multi-T plasma *at each deprojected shell*



How to fit multi-T plasmas

- Line spectra insensitive to details DEM within T-range of factor 2
- All DEMs in example have same <T> and almost indistinguishable spectrum

✂ ➔ bin T-range with steps of factor 2



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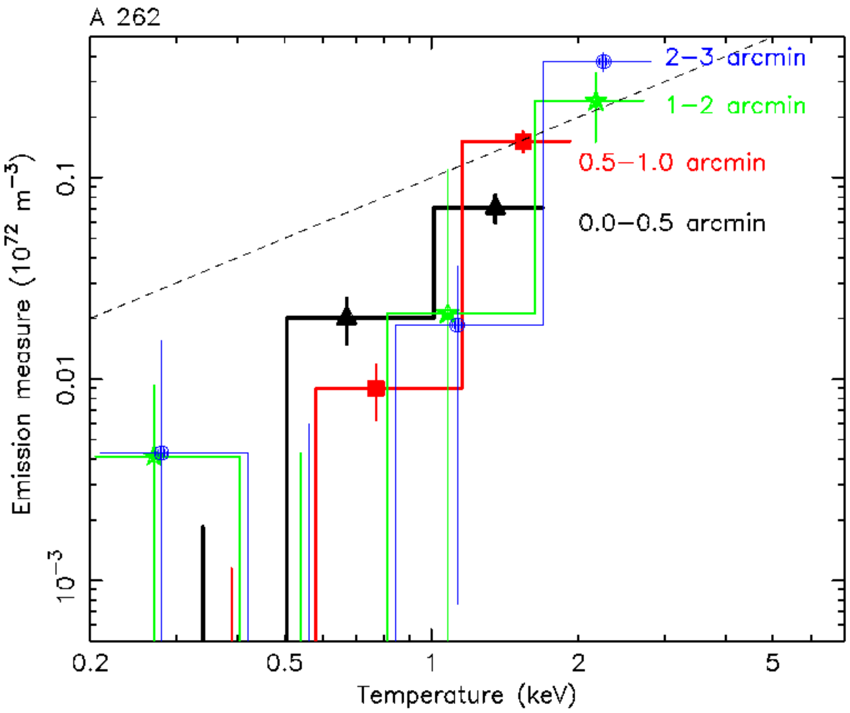
Multi-T gas at each radius

- Example: innermost 4 shells of A 262
- DEM steeper as expected from isobaric CF model
- T_{max} increases with r
- At each r multi-phase



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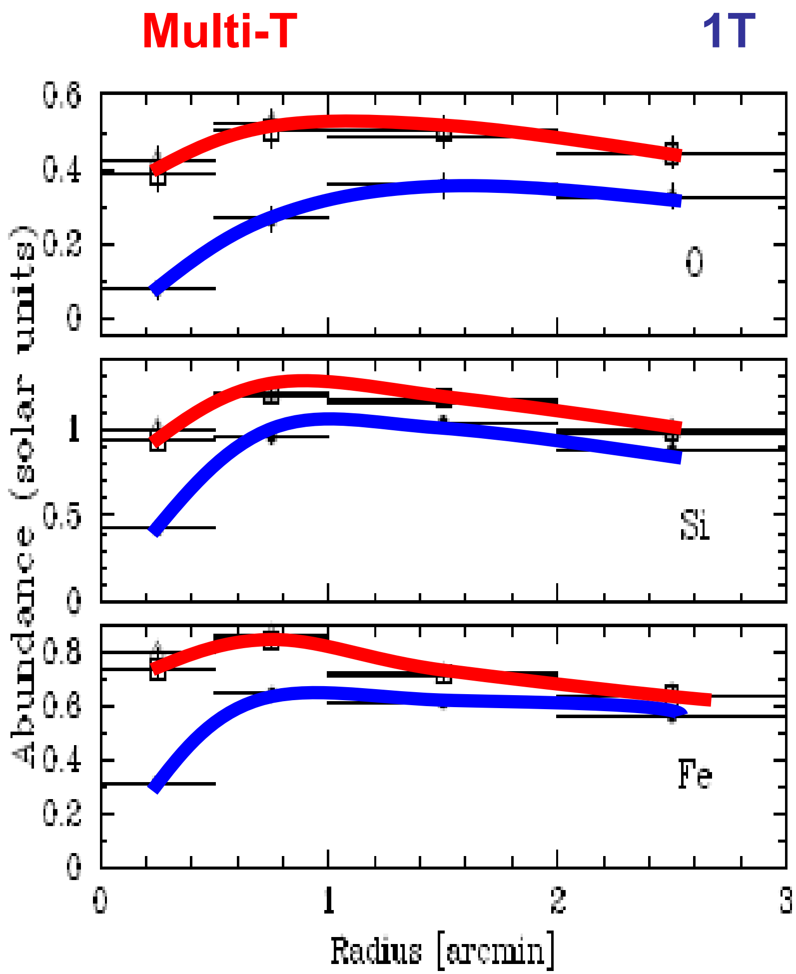
Some basics on biases in abundance estimates

The Fe bias

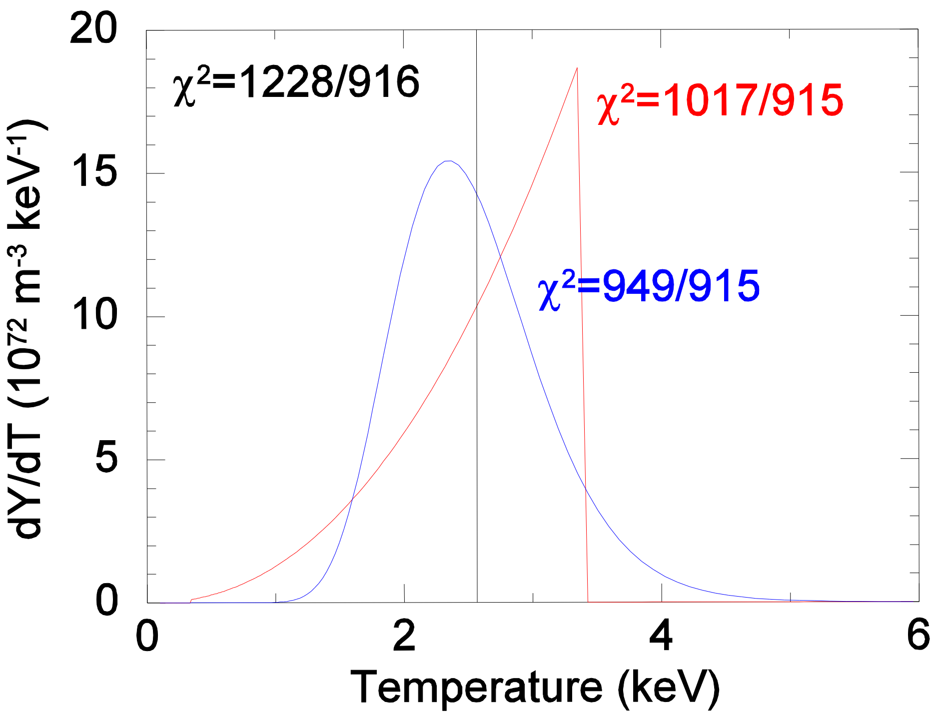
- 1T models sometimes too simple: e.g. in cool cores
- Using 1T gives biased abundances (“Fe-bias, Buote 2000)
- Example: core M87 (Molendi & Gastaldello 2001)



Complex temperature structure

(de Plaa et al. 2006)

- Sérsic 159-3, central 4 arcmin
- Better fits 1T➔wdem➔gdem
- *Implication for Fe:* 0.36➔0.35➔0.24
- *Implication for O:* 0.36➔0.30➔0.19



Implications for Fe abundance

(Simionescu et al. 2008)

Central 3 arcmin Hydra A, 1T models:

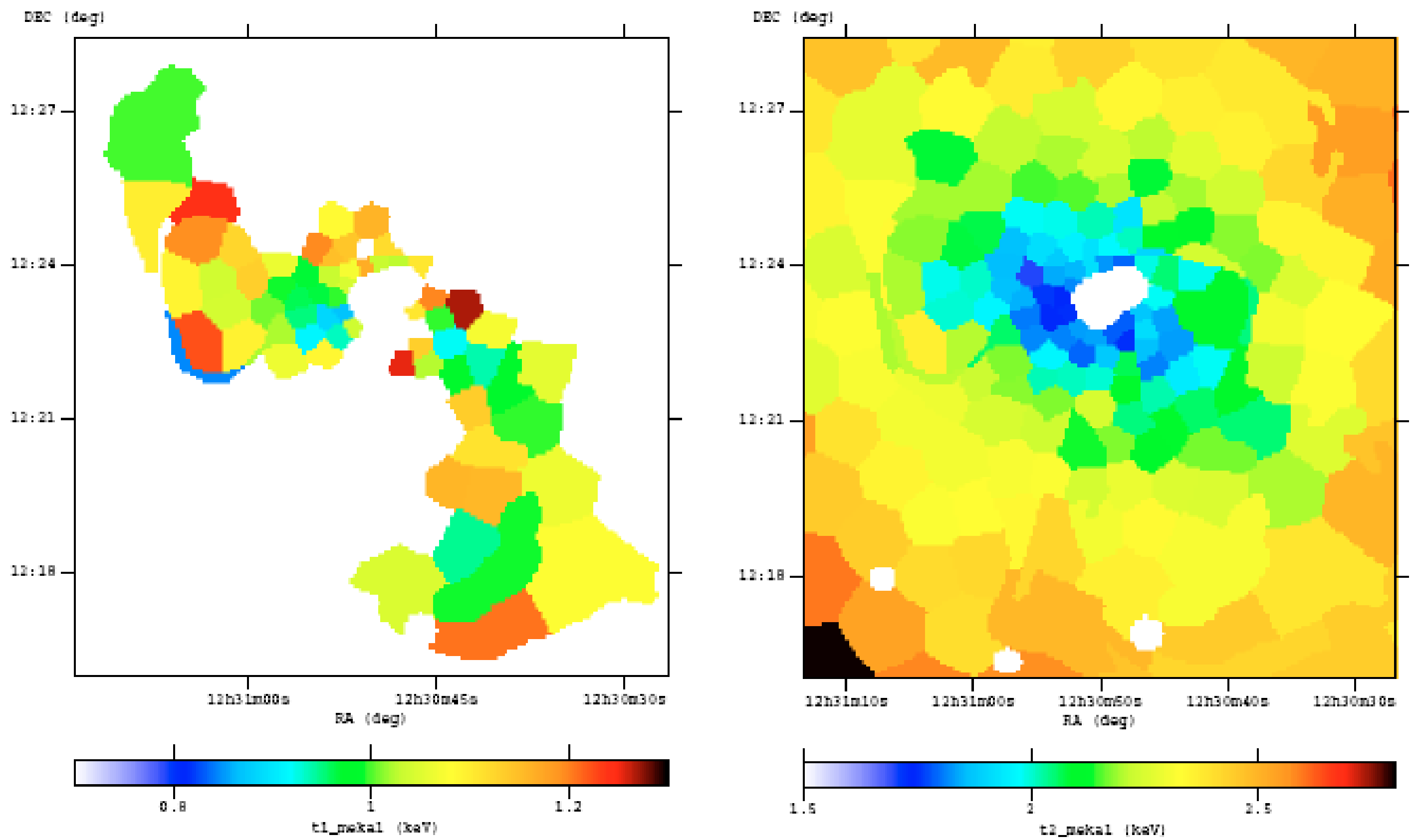
Band (keV)	kT (keV)	Fe
Full (0.35-10)	3.4	0.50
Low (Fe-L) 0.35-2	2.8	0.37
High (Fe-K) 2-7	3.9	0.41
Gdem	3.4, σ=0.2	0.45

(errors on Fe 0.01 to 0.02)

AGN feedback in action in clusters

Uplift of enriched material in M87/Virgo

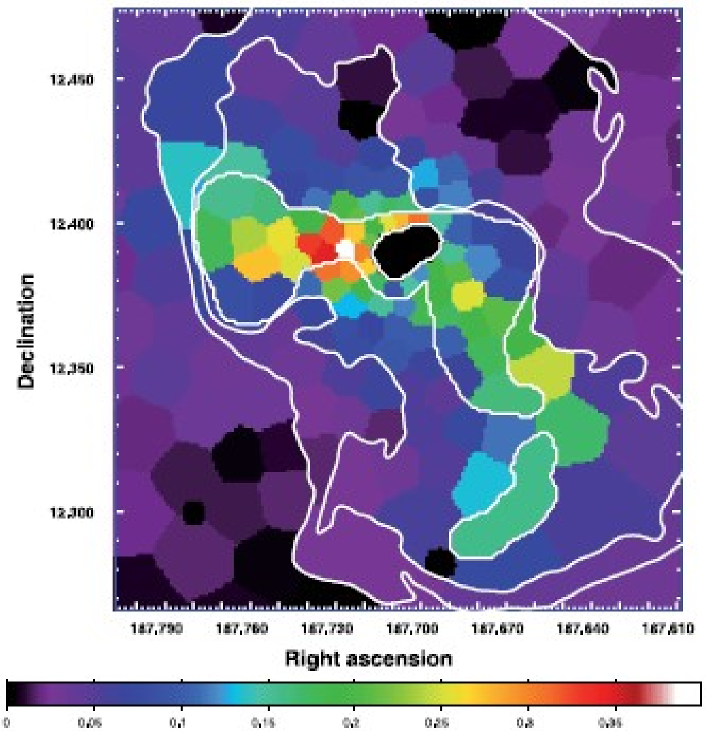
(Simionescu et al. 2008)



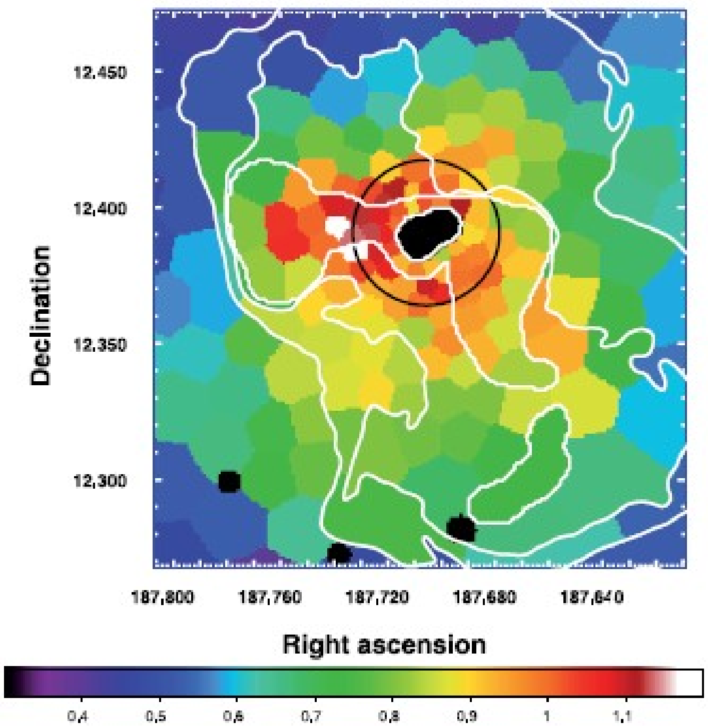
"Cold" gas ← 2T fits → "hot" gas

Uplift of cold, metal-rich gas in M87

(Simionescu et al. 2008)



Fraction of cold gas

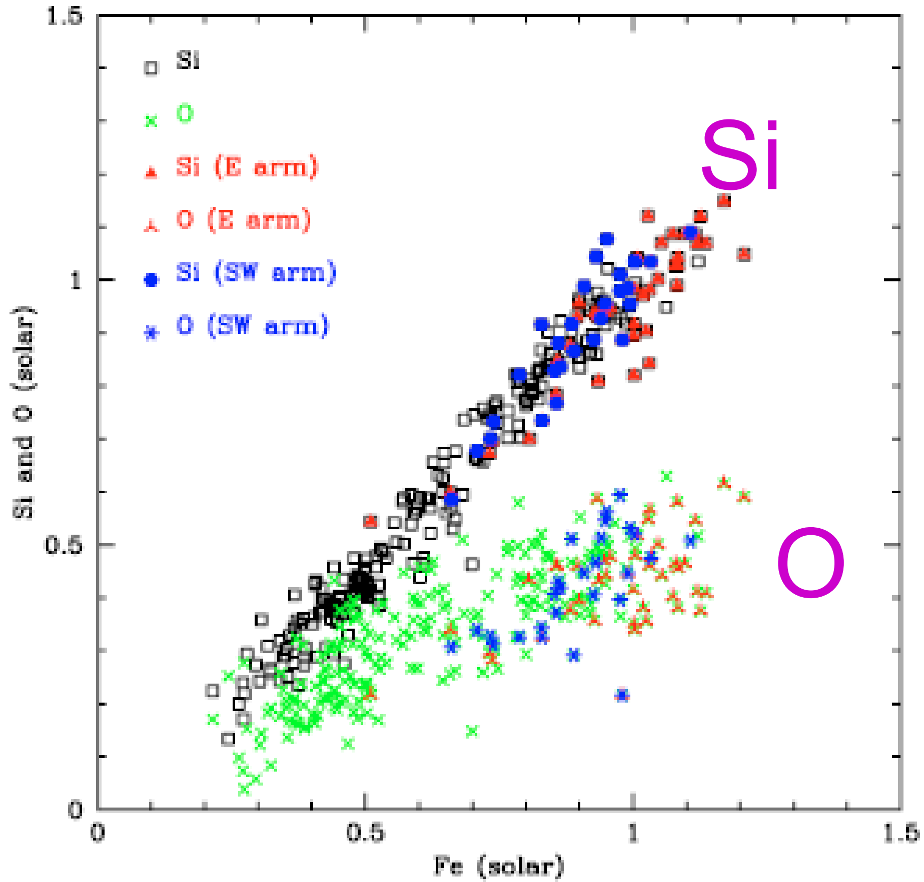


Iron abundance

Homogeneous composition

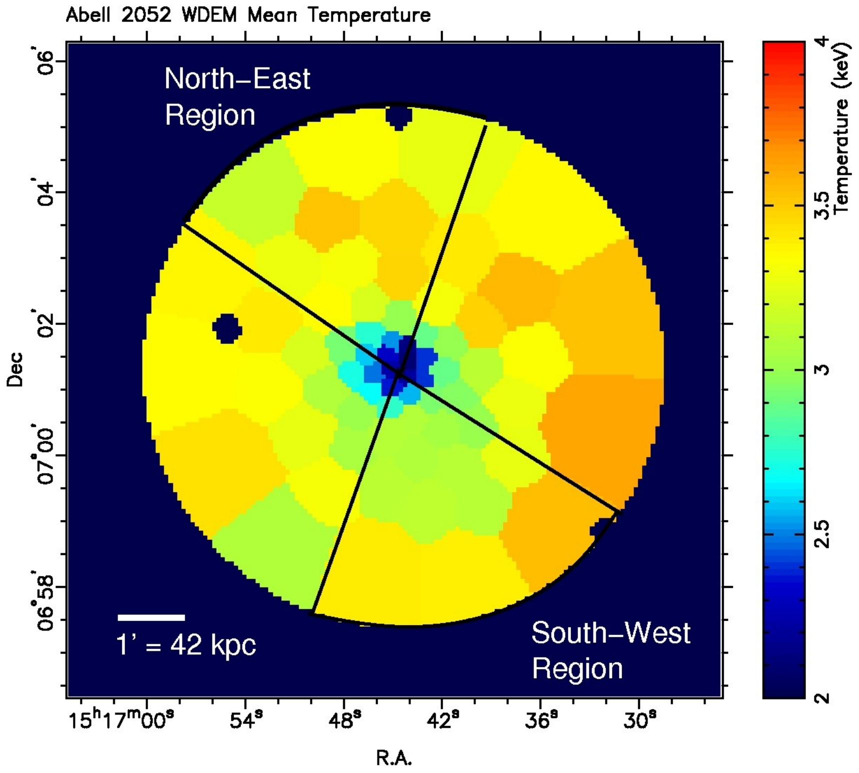
(Simionescu et al. 2008)

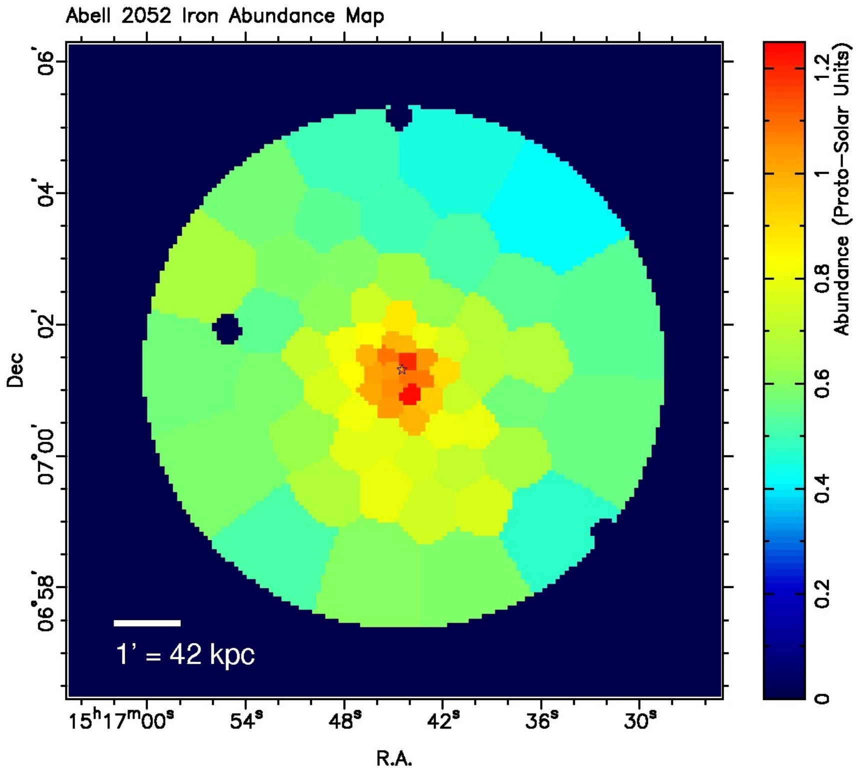
- Abundance ratio's O, Si and Fe are the same both inside and outside the arms ➔ recent AGN outbursts have uplifted the cold gas (about 5×10^8 Msun)



Sloshing central galaxy: cosmic mixer

(de Plaa et al. 2010)





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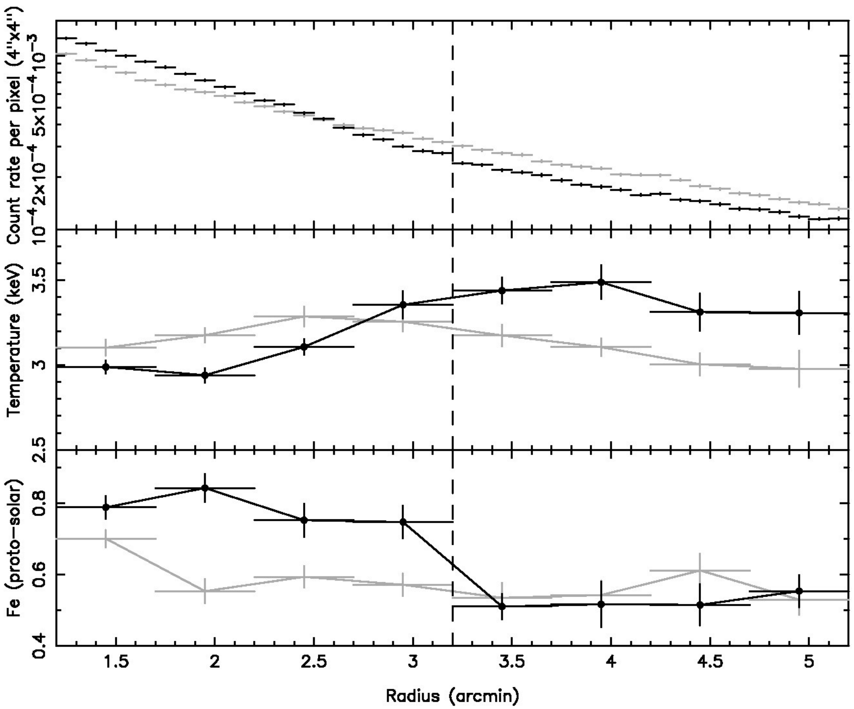
Sloshing in A 2052

(de Plaa et al. 2010)

- At 130 kpc from core in SW direction, sudden change from cold, metal-rich gas to hotter, metal poorer gas
- Boundary rather sharp
- Sloshing of hot gas in the potential well
- Mechanism to transoprt metals outward



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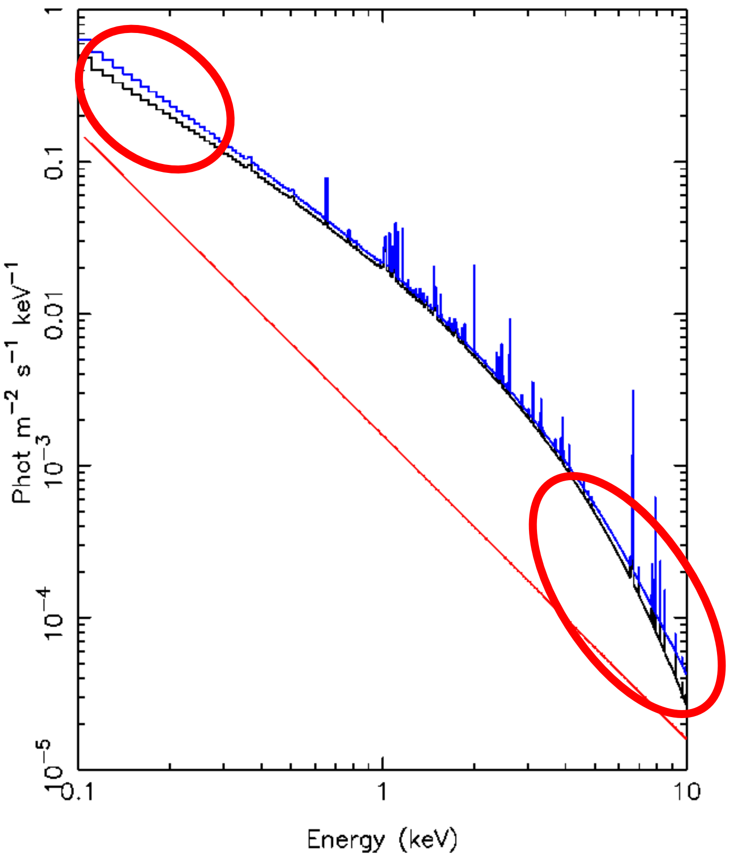
Soft and hard X-ray excesses

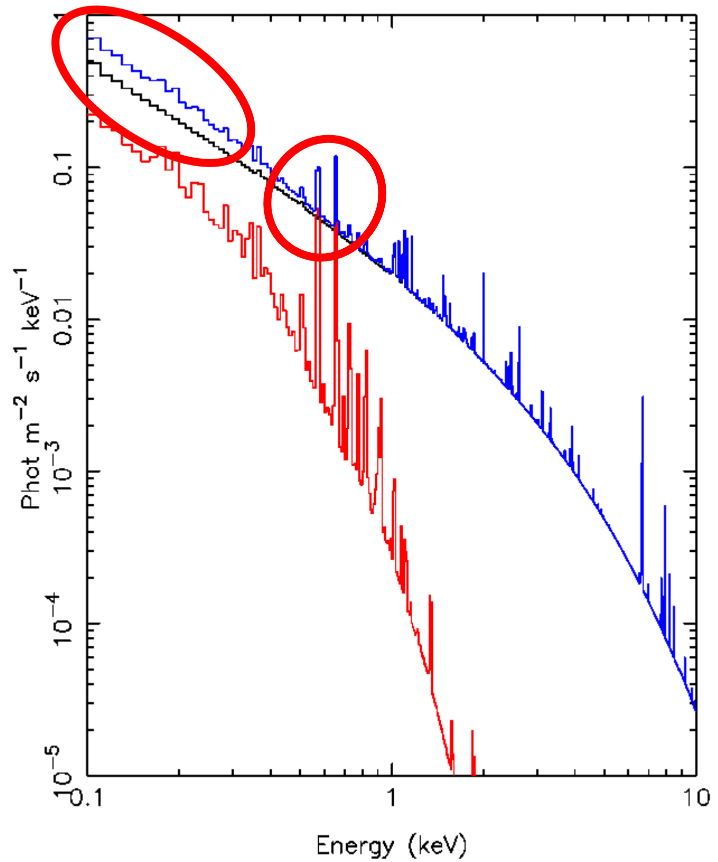
- Hot debates in literature
- Some *thermal* soft excess should be there in cluster outskirts (transition to WHIM)
- Here focus on non-thermal components:
  - May be related to AGN activity
  - Can "contaminate" the abundance determinations

Soft & hard excesses

Nonthermal excess



Thermal excess

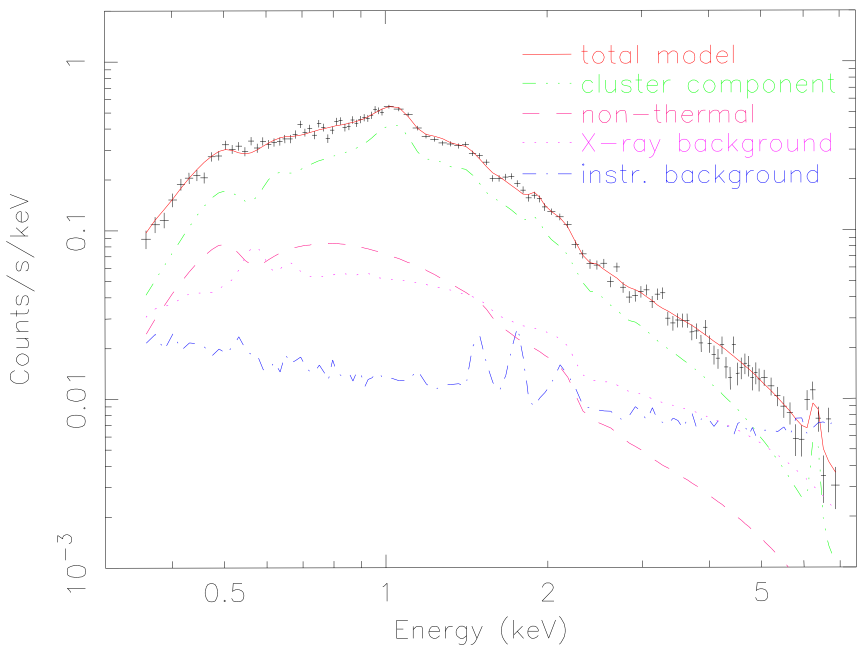


Suzaku spectra of Sérsic 159-3

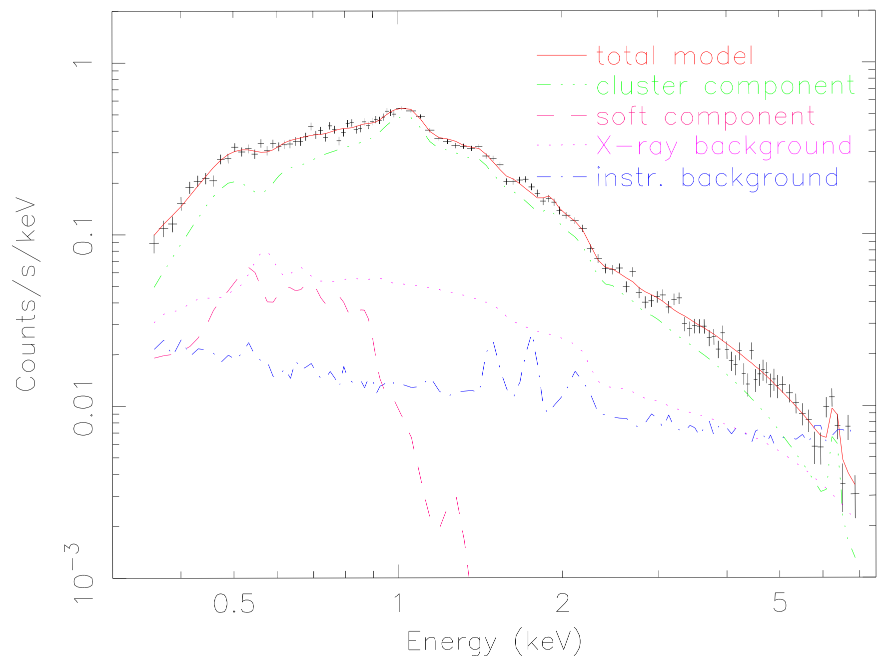
Werner et al. 2007

Both models are statistically acceptable

Nonthermal excess



Thermal excess



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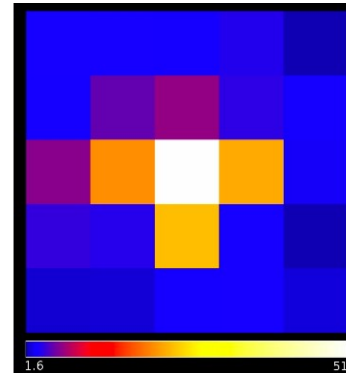
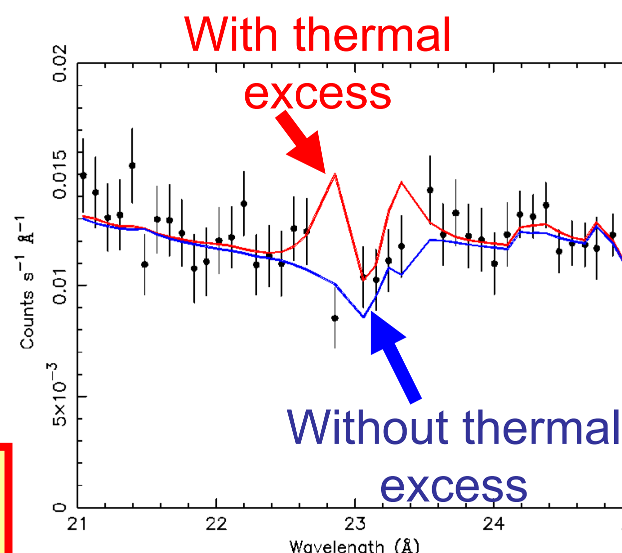
Nature of the soft excess

- Extended excess
- Peaks at core
- WHIM filament? No
- Warm ICM gas? No
- RGS spectrum: no O VII lines

→ most likely non-thermal (unless low metallicity)



Emission measure soft excess in 15x15 arcmin region around core



XMM-Newton RGS spectrum core

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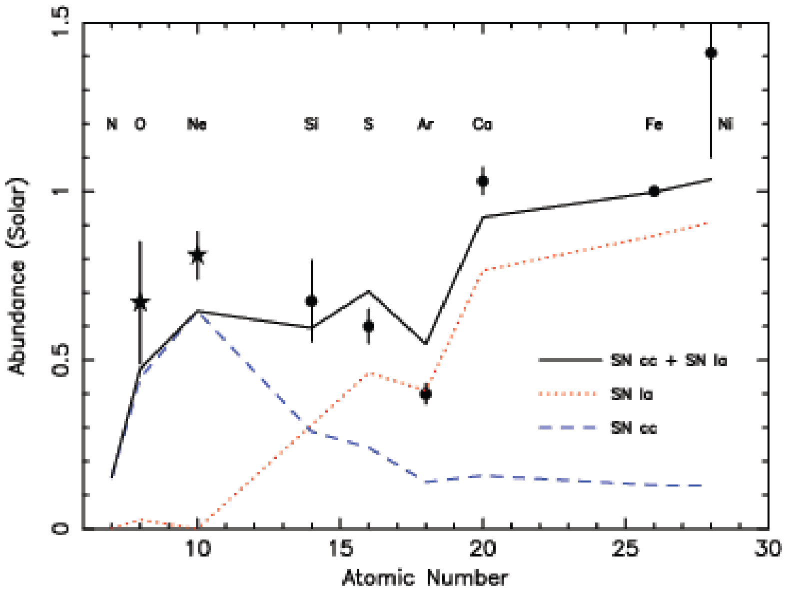
Final remarks

Nucleosynthesis in action in clusters

(De Plaa et al. 2007)

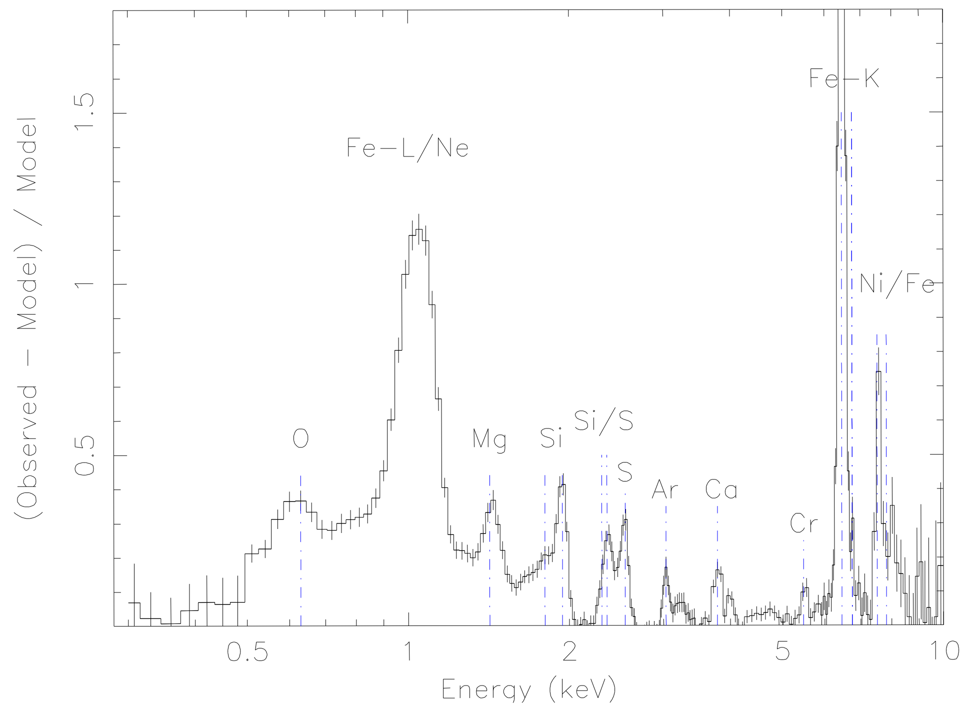
- 22 clusters, 685 ks net exposure time (8 days)
- Spectra of the cores
- Deviations individual elements solved (Ca)
- Need to do this spatialy resolved



Going deeper to get more elements

(Werner et al. 2006)

- Current best case: deep XMM-Newton observation of one of brightest clusters
- First evidence of traces of Cr (0.5±0.2 Solar)



2A 0335+096, Werner et al. 2005

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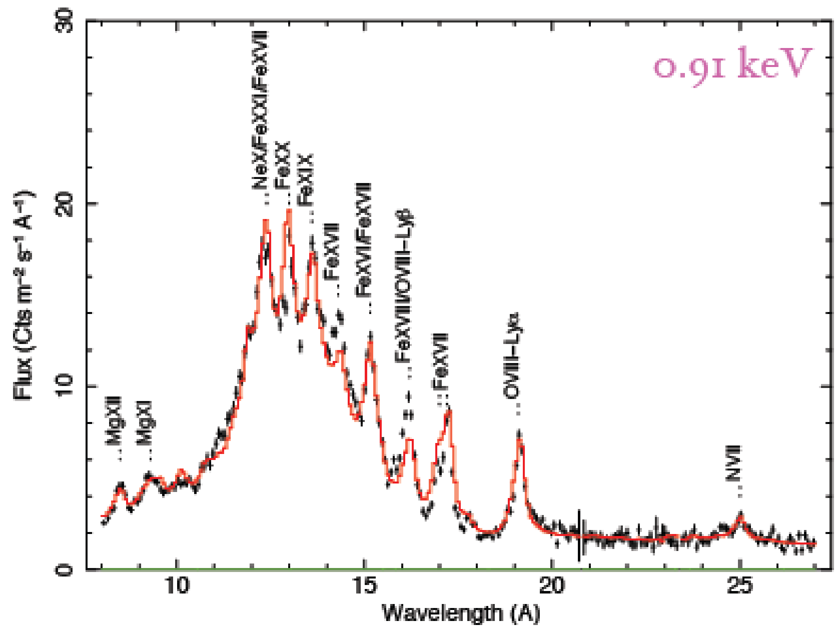
And of course role AGB stars

- Nitrogen and carbon mainly produced by intermediate mass stars
- Challenge for Xenia to map N and C!



NGC 5044

Grange et al. 2010

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Composition visible Universe

- Standard cosmological models:
- Volume 3.57×10^{80} m^3
- Average H density 0.182 m^{-3}

El.	#	El.	#
H	6.5×10^{79}	Si	1.1×10^{75}
He	6.2×10^{78}	S	4.2×10^{74}
C	8.2×10^{75}	Ar	6.5×10^{73}
N	5.0×10^{75}	Ca	1.0×10^{74}
O	1.3×10^{76}	Fe	1.3×10^{75}
Ne	3.5×10^{75}	Ni	1.1×10^{74}
Mg	9.7×10^{74}	**Sum**	$\mathbf{7.1 \times 10^{79}}$

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